BENTHIC HABITAT MAPPING OF PACIFIC OCEAN CORAL REEFS WITH HIGH-RESOLUTION SATELLITE IMAGERY*

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ABSTRACT

High-resolution, multispectral satellite imagery provides a potential capability to generate benthic habitat maps for remote, shallow water coral reef ecosystems, including those that are logistically difficult or prohibitively expensive to map by shipboard or aerial surveys. Commercially available, 4 m spatial resolution, multispectral imagery is used to create such maps for reefs in the Northwest Hawaiian islands (NWHI), part of a recently declared U.S. marine reserve. The multispectral nature of the imagery is exploited to minimize atmospheric and water surface effects and to generate true-color pictures and maps of bathymetry and bottom albedo. The water color, bathymetry and bottom albedo are incorporated into a rule-based classification process, using a hierarchical classification scheme. Geographical editing, based on available field data, is performed in advance and incorporated into the classification process, allowing map reproducibility. The NWHI atolls range from 100-700 km^2 in area, and the high spatial resolution of the imagery and digital processing allow for classification with a minimum mapping unit of <400 m^2. Benthic habitat data collected during a NWHI research cruise are used to validate the resulting maps. The results demonstrate that high-resolution satellite imagery and a rule-based classification system can be effective tools for mapping coral reef habitats.

* Presented at the Seventh International Conference on Remote Sensing for Marine and Coastal Environments, Miami, Florida, USA, 20-22 May 2002

1.0 INTRODUCTION

The U.S. has direct jurisdiction over more than 11,000 square kilometers of coral reefs in the Northwest Hawaiian Islands (Figure 1), more than 65% of all coral reefs in U.S. waters. As in other coastal regions, effective management of these areas requires habitat mapping, both to provide a baseline assessment of the ecosystem and to monitor its health over time. Interest in characterizing coral reef environments has increased recently, in response to widespread coral bleaching events, concerns over adverse human impacts, and growing interest in ecotourism. The increased management responsibilities associated with the recent declaration of the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve provide additional impetus for mapping coral reefs in that region. Mapping shallow water coral reef ecosystems is a challenging endeavor, especially when dealing with relatively large reef areas in remote island regions, and high resolution satellite imagery offers a potentially powerful and cost-effective tool for this effort. This study focuses on the use of commercially-available, multispectral satellite imagery, supplemented by field data, to map benthic habitats. The process is discussed in detail, with examples given for Kure Atoll, the last island on the Northwest Hawaii chain.

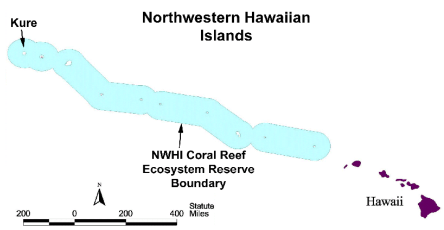

Figure 1. Main and Northwest Hawaiian Islands, with Marine Reserve Boundary

2.0 METHODS

2.1 DATA

High-resolution commercial satellite imagery was obtained for all of the NW Hawaiian Islands from Space Imagingís IKONOS satellite, constrained for cloud cover and sunglint. IKONOS has four multispectral bands (blue/green/red/near-IR) with 4 m spatial resolution and a panchromatic band with 1 m spatial resolution, across a maximum swath width of 11 km. The swath width is smaller than many of the NW Hawaii reefs, so multiple swaths were generated for most areas, but because the satellite can be pointed, the swaths were frequently collected on the same pass. Ground-control and *in situ* benthic habitat and bathymetry data were obtained during a National Ocean Service (NOS) research cruise to the NW Hawaiian Islands during Aug-Sep 2001. Preliminary true-color images were generated from the satellite data prior to the cruise, and the pictures provided both a navigational aid and a guide to effectively cover the variety of habitats present at each atoll. Additional information, primarily water depths from soundings, was obtained from large scale (1:10,000 to 1:40,000) nautical charts of the area. High-spatial resolution depth information was also obtained from lidar transects flown over several of the atolls.

2.2 GEOPOSITIONING

The imagery was initially positioned with an image processing program (PCI Geomaticaís OrthoEngine), using the satellite orbital parameters and yielding horizontal accuracies of <20 m near sea level. This positioning process was extremely efficient, generally taking less than an hour for a single swath of data. Individual georeferenced swaths were mosaicked together for most of the study areas and the positioning of the entire scene was then adjusted with the available ground control points. Nautical charts of the NW Hawaiian islands, with the exception of Midway, are positioned relative to astronomic datums, which can differ from satellite datums by hundreds of meters in this region, so ground control was not obtained from the charts, but from points collected by National Geodetic Survey (NGS) teams during the NW Hawaii cruise. The positioning adjustment was only a simple translation, since there are limited land areas and therefore few control points, and because evaluation of IKONOS scenes collected for the main Hawaiian islands indicated excellent intra-scene geometry. Digital elevation models (DEMS) were not available for land in this region, so areas with significant height were not positioned to the same accuracy as those near sea level. If available, DEMs can be easily incorporated into the process to improve the positioning. The red, green and blue band data were combined to create accurately mapped, true-color images as an initial product (Figure 2).

2.3 REFLECTANCE AND BATHYMETRY

We applied the radiometric calibrations provided by Space Imaging and derived remote sensing reflectance, which was then further corrected for both ocean surface and atmospheric effects, following Stumpf and Pennock (1989). The resulting reflectance data facilitate direct spectral comparisons between imagery bands and between imagery collected in different locations and at different times. In order to convert the reflectance just below the water surface to bottom albedo, we required water depth information, however this information was not available at sufficient spatial resolution or coverage for NW Hawaii. As an alternative, we calculated water depths from the reflectance data, using depth sounding information from the nautical charts for calibration. The bathymetry estimation uses a new method that improves the depth penetration over that of Lyzenga (1978), reaching depths of approximately 30 meters in clear water (Stumpf, *et al*, submitted). Where available, the bathymetry values were validated with lidar-derived depths obtained from aircraft overflights. The water depths were then used to correct the water reflectances, yielding an estimate of bottom albedo, which is a better parameter for discriminating habitat (Mumby *et al*, 1998).

2.4 CLASSIFICATION

Total and bottom reflectance, with the derived bathymetry, are then used to classify benthic habitat. Given the number of areas to be mapped (ten within NW Hawaii alone), the size of the shallow water areas (up to ~ 700 km^2 for a single atoll), the many small-scale features typical of coral reef environments, limited field access and the need for consistency, standard visual interpretation was not a viable option. We developed a rule-based approach that uses contextual and spatial information, as well as the spectral, bathymetric and externally-derived data. In addition, a hierarchical classification scheme (Table 1) was developed that optimizes the information available in the imagery and which can be easily incorporated into schemes developed for data collected with airborne and field surveys. The preliminary classifications were validated with benthic habitat data collected during the cruise, with an initial subset of the *in situ* data used to adjust the classes and an independent subset withheld for accuracy assessments on the final classifications.

Table 1. Draft Benthic Habitat Classification Scheme for NW Hawaii

- 1000 Unconsolidated Sediments (< 10% vegetation or hardbottom)
  - 1100 Sand
  - 1200 Carbonate Mud
  - 1300 Unconsolidated Rubble (predominately pebble- and cobble-size)
- 2000 Corals and Hardbottom
  - 2100 Corals (Colonized) hardbottom
    - 2110 Linear Reef
    - 2120 Spur and Groove
    - 2130 Individual Patch Reef
    - 2140 Aggregated Patch Reef
    - 2150 Individual Coral Heads
    - 2160 Aggregated Coral Heads
    - 2170 Coral-colonized pavement
    - 2180 Coral-colonized pavement with sand channels
    - 2190 Coral-colonized Volcanic Rock
  - 2200 Uncolonized Hardbottom
    - 2210 Linear Reef
    - 2220 Spur and Groove
    - 2230 Individual Patch Reef
    - 2240 Aggregated Patch Reef
    - 2270 Uncolonized pavement
    - 2280 Uncolonized pavement with sand channels
    - 2290 Uncolonized Volcanic Rock
  - 2300 Encrusting Coralline Algae (>10%, but < 10% coral)
    - 2310 Linear Reef, Continuous Encrusting/Coralline Algae
      - 2311 Intertidal reef crest
    - 2320 Spur and Groove,
    - 2330 Individual Encrusting coralline algae Patch Reef
    - 2340 Aggregated Patch Reef
    - 2350 Individual Coral Heads
    - 2360 Aggregated Coral Heads
    - 2370 Encrusting coral on pavement
    - 2380 Encrusting coral on pavement with sand channels
    - 2390 Encrusting coral on Volcanic Rock
- 3000 Submerged Vegetation
  - 3100 Seagrass Beds
    - 3101 Patchy seagrass (10-50% Cover)
    - 3102 Continuous Seagrass
  - 3200 Macralgae (fleshy and turf) Beds
    - 3201 Patchy (Discontinuous Macroalgae (10-50% Cover)
    - 3202 Continuous Macroalgae (50-100% Cover)
- 4000 Other Delineations
  - 4100 Land
  - 4200 Emergent Vegetation (mangrove)
  - 4300 Artificial
  - 4400 Unknown

3.0 RESULTS

A series of products are generated from this process, examples of which are provided here for Kure Atoll. Georeferenced true-color images, enhanced as necessary to show underwater features, provide a visual reference for the area (Figure 2). In addition to providing a high spatial resolution visual picture of the reef areas, these images can also be used for other purposes, such as identifying shorelines, and small, temporally varying sand islands, which can have dramatically different shapes and locations than those shown on nautical charts.

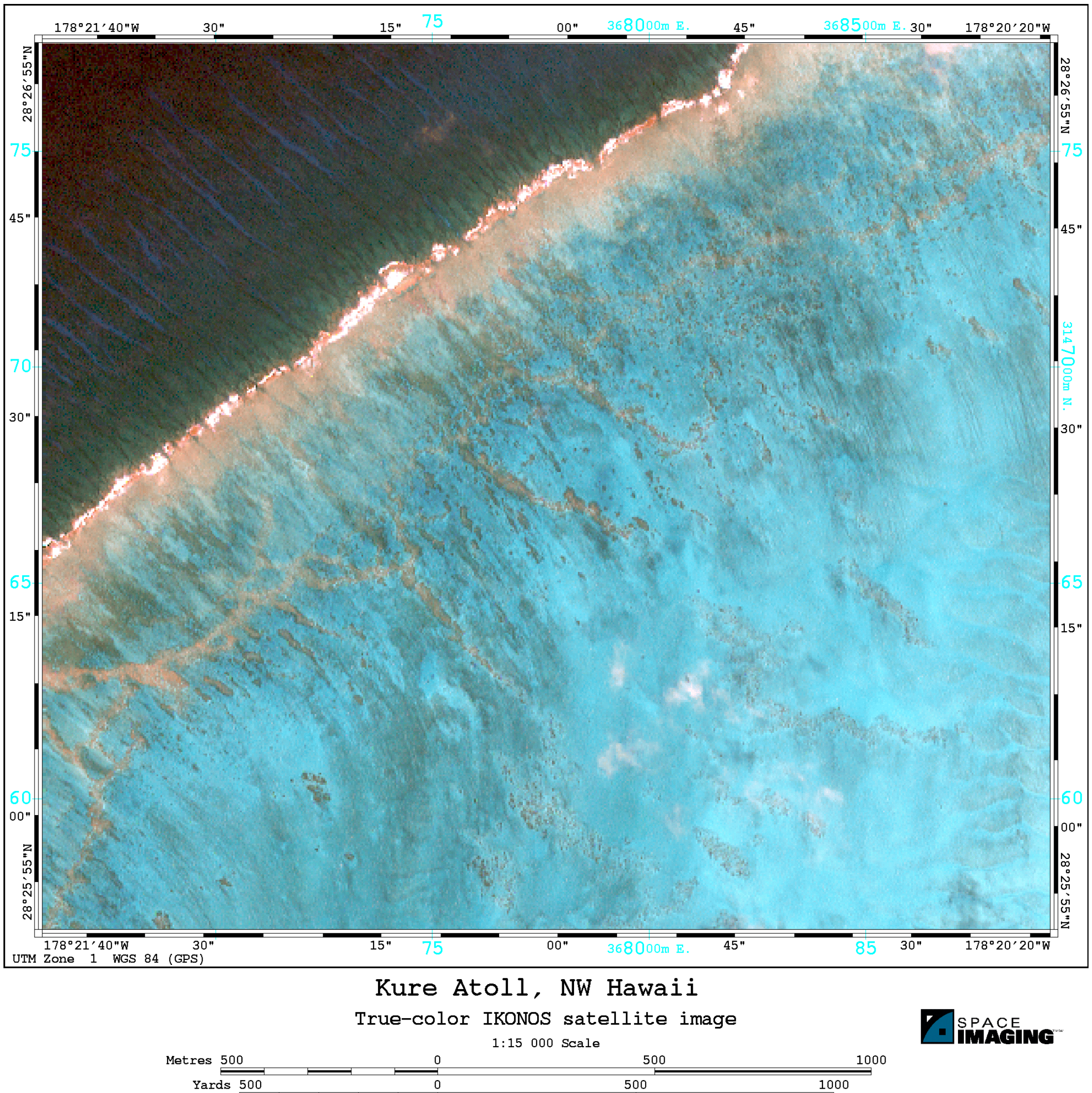

Figure 2. True-color IKONOS Satellite Image for Northwest Portion of Kure Atoll (including reef crest)

Maps of derived bathymetry (Figure 3) provide depth information at a resolution not available on the nautical charts (although not to the same accuracy), allowing identification of navigation hazards and vertical reef structures such as spur and groove. Bathymetric features as small as ~100 m^2 have been mapped.

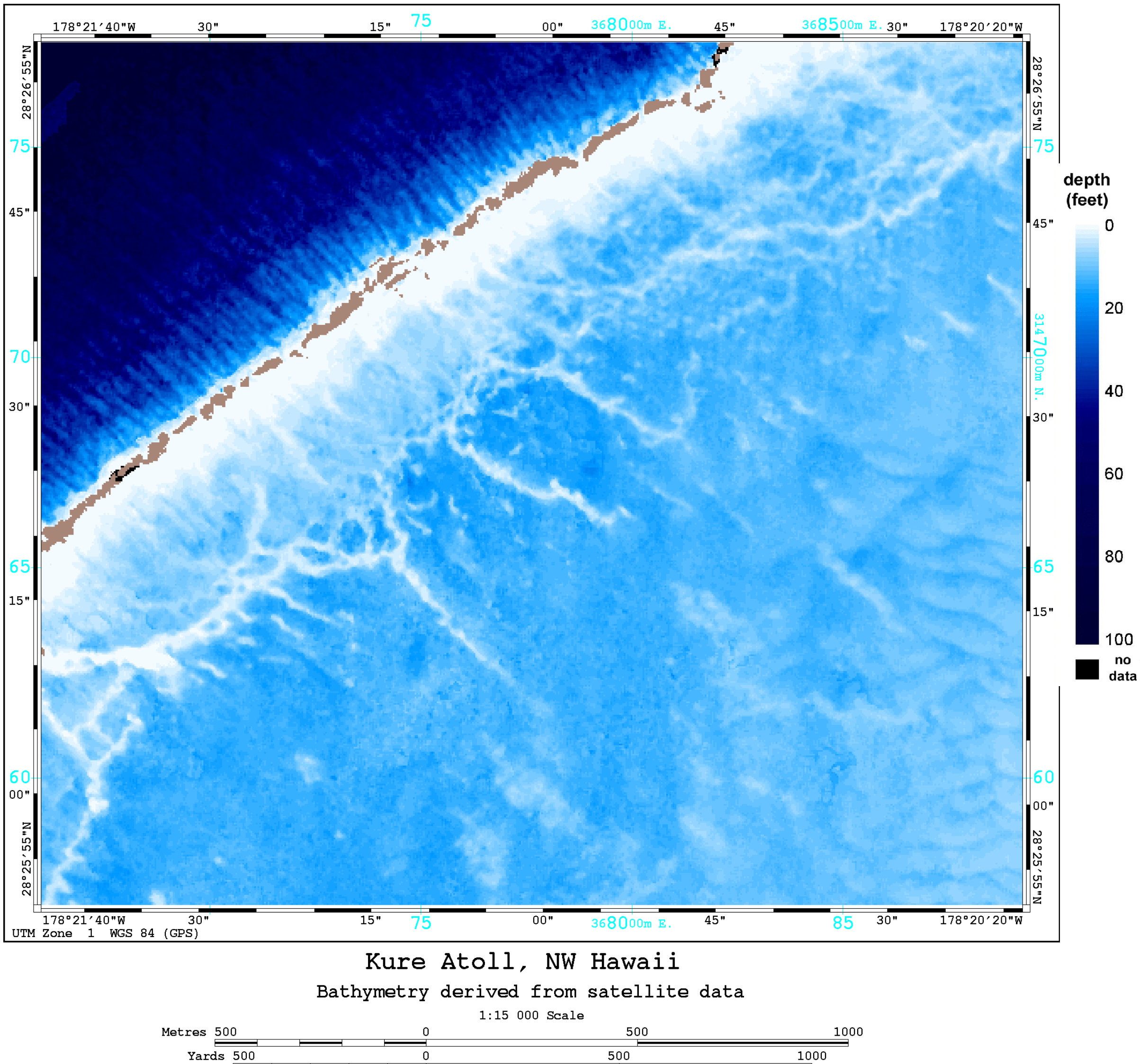

Figure 3. Bathymetry Derived From IKONOS Imagery for Kure Atoll (same view as Figure 2)

The habitat maps provide a detailed (Figure 4) initial description of the reef structure and benthic cover for relatively large reef areas (Figure 5). The rule-based process allowed us to achieve minimum mapping units of ~400 m^2 (0.1 acre), an order of magnitude smaller than what is typically obtained through visual interpretation. The hierarchical classification scheme allows identification of habitats down to a variety of levels, depending on the detail and degree of discrimination in the imagery and amount of field data available for confirmation. The use of multiple levels maximizes the amount of useful information obtained from the imagery and also facilitates improvement of the maps as additional data becomes available. The draft classification maps can be easily refined, if necessary, incorporating information obtained through field surveys, additional imagery acquisitions, and possibly airborne surveys for the less remote areas.

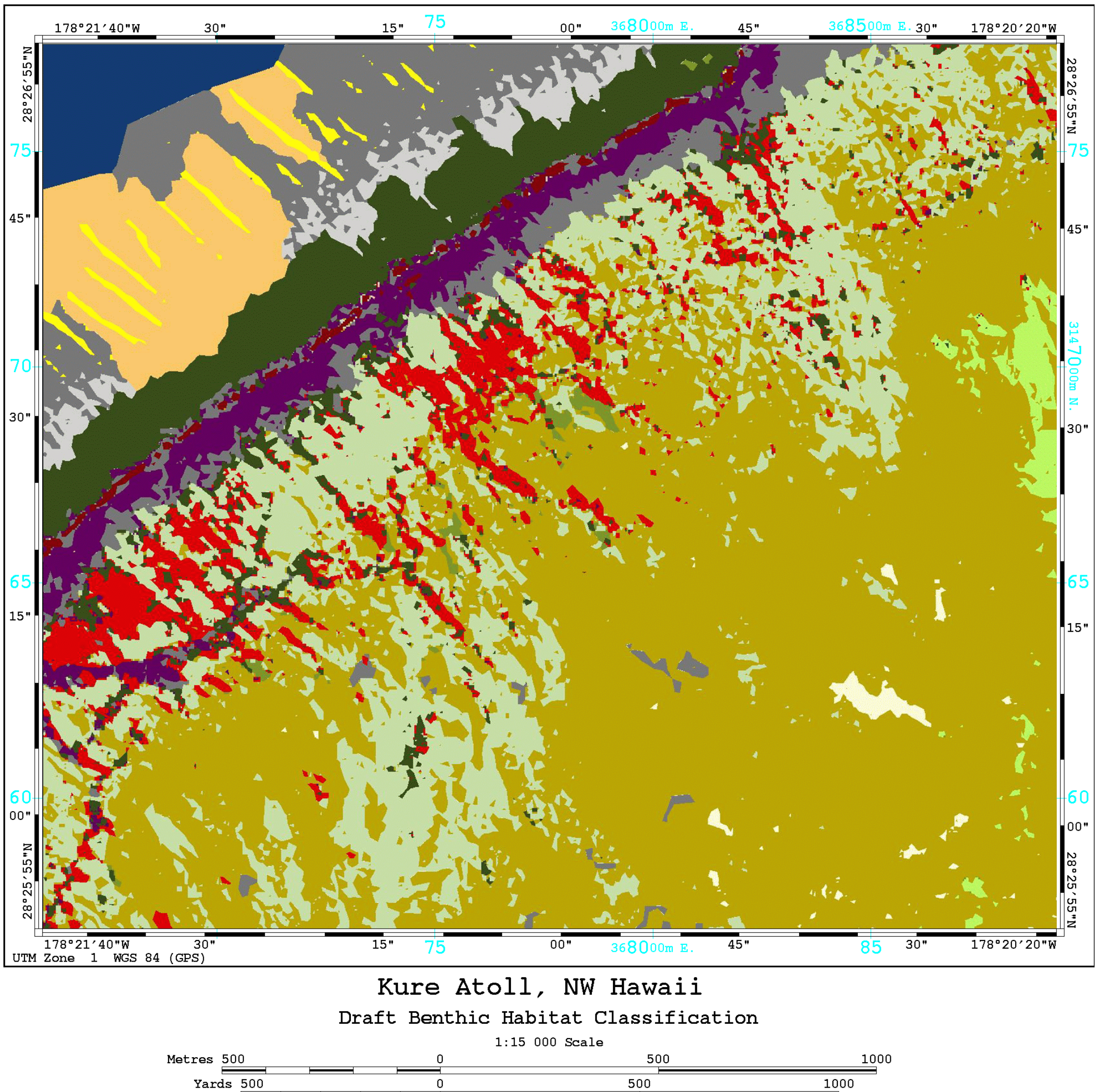

Figure 4. Draft Benthic Habitat Map for Kure Atoll (same view as Figure 2, see Figure 5 for legend)

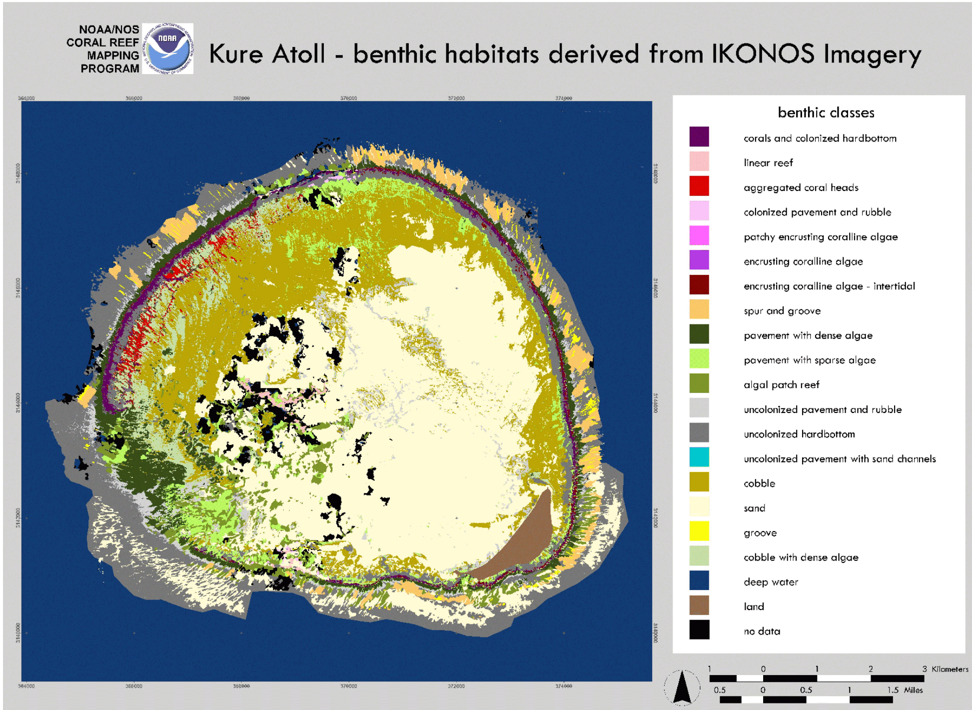

Figure 5. Draft Benthic Habitat Map for Kure Atoll

4.0 SUMMARY

Efficient benthic habitat mapping of large, remote coral reef regions, such as the NW Hawaiian islands, requires cost-effective techniques with sufficient spatial coverage and resolution to identify features of interest. High spatial resolution, accurately positioned, multispectral satellite imagery offers the type of information required for these areas. Use of image processing software that can classify both spectral and spatial characteristics of the data maximizes the amount of information obtained from the imagery. Application of digital, rule-based procedures and a hierarchical classification scheme allow for efficient habitat classification, with a small minimum mapping unit, timely classification of multiple areas, and map reproducibility. IKONOS multispectral imagery was used to demonstrate this capability for NW Hawaiian reefs, yielding georeferenced images and bathymetry and draft habitat classification maps that show great promise for resource management needs.

5.0 REFERENCES

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